The Use of Knowledge-Based Engineering Systems and Artificial Intelligence in Product Development: A Snapshot

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Abstract. Beside the creative activities in product development, the design process involves multiple routine tasks that are subject to automation. Techniques like knowledge-based engineering, what is commonly understood as the merging of computer-aided design, object-oriented programming and artificial intelligence, have been discussed since years, but have not yet achieved a significant breakthrough. But in particular the actual debate on digitization and artificial intelligence draws much attention on fostering new automation potentials in design of products and services. This article aims at taking an actual snapshot in which fields of application knowledge-based engineering systems and artificial intelligence are used in product development. Therefore, the authors conducted a systematic literature review, limited to scientific literature of the last five years. The literature analysis and synthesis is condensed within a concept matrix that documents actual applications and shows further research potentials.

Keywords: Knowledge-based engineering · Artificial intelligence · Product development

1 Introduction

Product development and design problem solving are structured activities aimed at transforming technical and design requirements into a product specification, including geometric models, production data and assembly instructions [1]. It strongly depends on the experience and skills of the designer, i.e. finding suitable solution concepts, making an initial embodiment design and detailing parts and assemblies according to existing restrictions, e.g. from manufacturing or logistics [2]. Beside these creative tasks, the design process involves different routine tasks that are today subject of automation, like e.g. product configuration [3].

Techniques like knowledge-based engineering (KBE) have been discussed since years, but have not yet achieved a significant breakthrough beside single niche design activities like fixture design or applications in aerospace or automotive development [4].

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Nonetheless, the vision of Chapman and Pinfold who understand KBE as "evolutionary step in computer-aided-engineering and (…) engineering method that represents a merging of object-oriented programming, artificial intelligence and CAD technologies, giving benefit to customized or variant design automation solutions" [5] is today more relevant than ever. A reason for this are the emerging methods and tools in the field of artificial intelligence.

This article aims to provide a snapshot how actual developments in knowledge-based engineering systems (KBES) and artificial intelligence disseminate in product development. Therefore, the authors conducted a systematic literature review, limited to scientific literature of the last five years. In the following Sect. 2, related work is presented in order to contextualize this study mainly in the field of knowledge-based engineering and product development. In Sect. 3, the methodology for the literature analysis is introduced. Afterwards in Sect. 4, the results of literature analysis and synthesis are presented and further discussed in Sect. 5. The final Sect. 6 concludes the article and presents a brief research agenda.

2 Related Work

KBE is founded on research on knowledge-based systems that have to be understood as computer aided problem solving tools. Problem solving behavior is generally modelled on that of a human expert, so the term *expert systems* developed as a synonym for knowledge-based systems of all kinds, particularly in the 1980s and 1990s. Examples include assistance or diagnostic systems in medicine, speech recognition tools and automatic classification systems [6].

In particular in engineering, expert systems were originally designed for product configuration [7] and design automation in special fields like in fixture design [8]. The rise of parametric CAD systems that allow defining variable geometric models led to new possibilities in knowledge integration within digital prototypes, like the implementation of design rules, dimensioning formulae or automated routines for geometry creation [2]. The modelling focus thus shifts from a single solution or product variant to a solution space or set of variants [9].

In order to support designers in the (commonly manual) formalization of knowledge and the creation of KBE applications, different process models and design methods, like e.g. KADS or MOKA have been proposed on the one hand [10, 11]. On the other hand, the use of artificial intelligence, like solving of constraint satisfaction problems, changed and extended the way solution spaces were modelled [12, 13].

Foundational research in knowledge-based systems and artificial intelligence dates back to the 1980s and 1990s where the available computing power was not sufficient to model and solve real world problems in the design engineering domain. Today, this lack of power seems overcome and emerging technologies like machine learning etc. extend the possibilities. Taking into account the burst of research in these fields of the last years, the authors want to investigate the dissemination of current research form KBE and artificial intelligence to product development, especially regarding the early phase of the product development process.

3 Methodology

In order to show which fields of application exist for knowledge-based engineering systems (KBES) and artificial intelligence in product development, the authors conducted a detailed literature search, following the methodological recommendations of vom Brocke et al. [14] as well as Webster and Watson [15]. The subsequent listing shows the different phases and their assignment to the sections: (I) definition of review scope, (II) conceptualization of topic, (III) literature search, (IV) literature analysis and synthesis and (V) research agenda.

Table 1. Search strategy and hits in Google Scholar

Search phrase	Product development	Production engineering	Manufacturing	Customization	Simulation	Optimization	roduct service system	Lifecycle	Modularization	Solution space	Product generation	Cyber physical system	Design	Modelling	Computer aided design	$\sum$	Pages
Knowledge-based	18	14	5	14	4	22	12	20	5	13	0	13	1	1	11	**153**	10
Artificial intelligence	15	12	9	4	4	4	6	2	8	0	4	2	4	1	2	**77**	10
Machine learning	3	3	2	0	2	4	2	1	2	0	2	2	4	1	1	**29**	3
Deep learning	0	0	1	0	0	0	0	0	0	0	0	1	0	1	0	**3**	3
Rule-based	3	3	1	0	0	3	0	0	0	1	0	0	4	0	0	**15**	1
Case-based	3	1	2	1	1	0	3	2	0	0	1	1	2	0	0	**17**	1
Constraint-based	4	0	0	0	0	0	1	2	1	2	0	1	0	0	0	**11**	1
Model-based	3	2	1	0	0	1	3	3	4	1	0	0	0	0	0	**18**	1
Agent-based	1	1	0	2	0	0	0	0	0	0	0	0	0	0	2	**6**	1
Cognitive	0	0	2	1	0	0	1	0	0	0	0	0	0	0	0	**4**	1
Ontology-based	0	1	0	1	0	0	2	0	0	1	0	0	0	0	0	**5**	1
$\sum$	**50**	**37**	**23**	**23**	**11**	**34**	**30**	**30**	**20**	**18**	**7**	**20**	**15**	**4**	**16**	**338**	

Additionally, the review was divided in two parts. First, suitable literature, with reference to artificial intelligence and knowledge-based engineering, was searched in the Scientific Society for Product Development (WiGeP).

In the analysis of the literature identified, the following search directions were distinguished: knowledge-based engineering (KBE), design optimization, simulation, product-service-systems (PSS), cyber physical production systems (CPPS), product generation and smart products. Based on these findings, the keywords were analyzed and combined to search phrases (Table 1). Second, a Google Scholar search was conducted using the search phrases to get a broad and interdisciplinary overview of the state of the art in computer science. The literature found was assessed according to its relevance for our research.

The search phrases consist of a method (vertical phrases) and an application (horizontal phrases). Based on the frequency of keywords in the WiGeP literature, the methods were divided into three levels to ensure a suitable search depth for Google Scholar. The first level comprises the generic phrases artificial intelligence and knowledge-based. The second level includes the common phrases machine learning and deep learning. The third level describes concrete methods such as case-based, agent-based or ontology-based. Due to a continuous, decreasing matching of the three method levels with our research purpose, we have adapted the search pages considered on Google Scholar, as described in Table 1. In order to get an actual snapshot, only literature of the last five years was included.

As shown in Table 1, product development plays an important role with 50 hits. Other important application areas are production engineering (n = 37) and optimization (n = 34). These results show a high importance for the practical application.

4 Literature Analysis and Synthesis

4.1 Classification of Results

We found 561 articles with the search method we used (Fig. 1). Of these, 223 were found among the members of the Scientific Society for Product Development (WiGeP). Another 338 articles were found by the method described in Sect. 3 on Google Scholar. As suggested by Webster and Watson [15], a complete keyword search and an evaluation of titles and abstracts was performed for each article (Evaluation I). Non-relevant articles were excluded for further consideration. The remaining 46 articles were verified as full text and selected after use in the early phase of the product development process (Evaluation II).

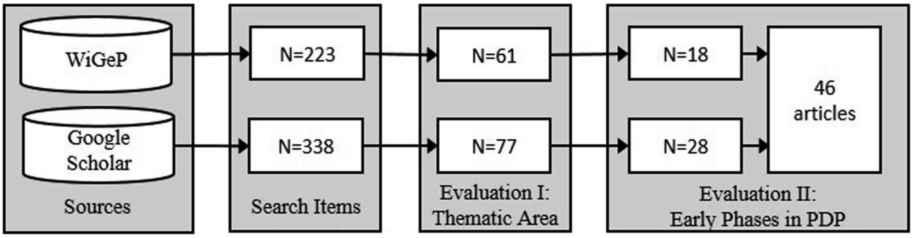

Fig. 1. Overview of search process

All relevant sources are listed in Table 2. Each article is provided with an *ID* (consecutive number), a *Reference* (article authors) and an assignment, whether the relevant articles present a *Methodology* (54%), show an *Application* (74%; further decomposed to conceptual modelling and presentation of relevant use cases) or present an *Algorithm* (22%). Multiple assignments were accepted.

Table 2. Overview of relevant articles

[ID]	Reference	Methodology	Application		Algorithm
			Conceptual	Use case	
01	Gembarski et al. [4]	-	-	●	-
02	Martins and Anderl [16]	-	-	●	●
03	Furian et al. [17]	-	-	●	-
04	Gembarski [9]	●	-	●	-
05	Konrad et al. [18]	●	-	-	-
06	Fender et al. [19]	●	-	-	●
07	Graff et al. [20]	●	-	-	-
08	Müller et al. [21]	●	-	●	-
09	Colombo et al. [22]	-	●	-	-
10	Chenchurin et al. [23]	-	●	-	-
11	Luft et al. [24]	●	●	-	-
12	Oellrich [25]	-	●	-	-
13	Hjertberg et al. [26]	●	-	-	-
14	Relich et al. [27]	-	●	-	-
15	Gembarski et al. [28]	-	●	-	-
16	Zhang et al. [29]	●	-	-	-
17	Zeng et al. [30]	-	-	●	-
18	Levandowski et al. [31]	●	-	●	-
19	Borjesson and Hölttä-Otto [32]	-	●	-	●
20	Garg [33]	-	●	-	●
21	Baykasoğlu and Ozsoydan [34]	-	●	-	●
22	Temple et al. [35]	-	●	-	●
23	Fuge et al. [36]	-	-	-	●
24	Abdeen et al. [37]	-	-	-	●
25	Debreceni et al. [38]	-	-	-	●
26	Zhu et al. [39]	-	-	-	●
27	Althuizen and Wierenga [40]	●	-	-	-
28	Hashemi et al. [41]	●	●	-	-
29	Moreno et al. [42]	●	-	-	-
30	Gembarski et al. [43]	●	●	-	-
31	Brem and Wolfram [44]	●	-	-	-
32	Biskjaer et al. [45]	-	●	-	-
33	Münzer [46]	●	-	●	-
34	Wang and Yu [47]	●	-	●	-
35	Yu et al. [48]	●	-	-	-
36	Pan et al. [49]	●	-	●	-
37	Trehan et al. [50]	-	●	-	-
38	Hagenreiner and Köhler [51]	●	-	●	-
39	Relich [52]	●	-	-	-
40	Hu et al. [53]	●	-	●	-
41	Chen et al. [54]	-	●	-	-
42	Fougères and Ostrosi [55]	●	●	-	-
43	Siqueira et al. [56]	●	●	-	-
44	Gembarski et al. [57]	●	●	-	-
45	Brockmöller et al. [58]	●	●	●	-
46	Bibani et al. [59]	-	●	●	-

4.2 Synthesis of Applications

Next, we classified the articles using a concept matrix (Table 3) divided into three dimensions: *Category/Applications* (determined from the articles), *Product Model* and

Table 3. Resulting concept matrix.

Category/Applications		Product model							Appearance in reference [ID]
		①	②	③	④	⑤	⑥	⑦	
Methods	Constraint-Satisfaction-Problem (CSP)	●	-	-	●	-	●	-	14, 22, 33, 39
	Theory of Inventive Problem Solving (TRIZ)	-	-	-	-	●	●	-	10
	Hazard Analysis	●	●	-	●	●	-	-	8
	Design Structure Matrix (DSM)	-	-	-	●	-	-	-	18, 19
	Modular Function Deployment (MFD)	●	●	-	-	-	-	-	19
	Case-based Reasoning (CBR)	-	-	-	●	●	-	●	26, 27, 28, 40, 43, 46
	Solution Space Exploration	-	-	-	●	●	●	-	4, 6, 7, 16, 24, 25, 32, 33, 41
	Design Methods	●	●	●	-	-	-	-	12, 23, 29, 30, 31, 45
Tools	*Software*								
	Computer-Aided Design (CAD)	-	-	-	●	●	●	●	2, 4, 9, 10, 11, 15, 17, 30, 36, 38, 42, 43, 44, 45, 46
	Finite Element Method (FEM)	-	-	-	-	●	●	-	36, 43
	Algorithm								
	Feature Recognition	-	-	-	●	●	-	-	2, 34, 42
	Artificial Bee Colony (ABC) Algorithm	-	-	-	-	●	-	-	20
	Firefly Algorithm	-	-	-	-	●	-	-	21
	Genetic Algorithm	-	-	-	-	●	-	-	24
	Fuzzy Neural Networks (FNN)	●	-	-	-	-	-	-	14, 39
	Artificial Neural Networks (ANN)	●	-	-	-	-	-	-	39
	Cluster Algorithm	-	-	-	-	●	-	-	26
	Data Mining	-	●	-	-	-	-	-	5
Processes	Knowledge-Based Engineering (KBE)	-	-	-	●	●	●	●	1, 4, 9, 11, 15, 30, 37, 38, 44, 45, 46
	Variant Management	-	●	-	●	●	●	-	4, 5
	Product Portfolio Management	●	●	-	●	-	-	-	14, 19
	Product Lines	-	-	-	●	●	●	-	17, 22
	Configuration Management	-	●	-	-	●	-	-	5, 16
	Knowledge Management	-	-	-	-	●	●	●	3, 9, 11, 13, 45
Design support	Decision Making	-	-	-	-	●	●	●	3, 45
	Problem Solving	-	-	-	-	●	●	●	3
	Design Automation	-	-	-	●	●	●	-	1, 34, 37
	Parametrization	-	-	-	●	●	●	-	2, 15, 33, 35, 40, 43
	Modularization	-	-	-	●	-	-	-	18
	Design Optimization	-	-	-	-	●	●	-	20, 21, 24, 38
	Assistance System	-	-	-	●	●	●	●	3, 10
	Agent-Based Modeling	-	-	●	●	●	-	-	41, 42
	Coverage (Count)	7	7	2	16	23	15	7	

① List of Requirements; ② Function, Function Structure; ③ Principle of Action, Structure of Action; ④ Building Structure; ⑤ Preliminary Design; ⑥ Overall Design; ⑦ Part and Assembly Drawings, other Documentation.

Appearance in Reference (source of the applications). Each of the 32 applications can be described by characteristics and were assigned to one of the following groups: *Methods*, *Tools*, *Processes* and *Design Support*.

The product models were chosen according to VDI Guideline 2221:1993 [60], which structures the product development process into four phases and seven product models: *Task Clarification* (List of Requirements), *Concept* (Function, Function Structure, Principle of Action, Structure of Action), *Embodiment Design* (Building Structure, Preliminary Design, Overall Design) and *Detailed Design* (Part and Assembly Drawings, other Documentation).

The concept matrix shows that 70% of applications for KBES and artificial intelligence in product development are used in the embodiment design phase. The concept phase accounts for 12% of the applications, whereby the Principles of Action and Structures of Action are strongly underrepresented with 3%. The detailed design phase seems underrepresented as well with only 9% of appearance.

5 Discussion

Interestingly, the methods block is the only one with a well-balanced distribution where all phases and product models are addressed. Regarding tools, a lot of CAD-centric articles were found but only a few which document holistic engineering environments that encompass synthesis as well as analysis tools, like FEM simulations. With respect to the application of distinct algorithms, some are used for task clarification, where the goal is to predict a new product success (e.g. refer to [27, 52]). Others support the preliminary design, e.g. as optimization algorithms.

In design support, the designer is usually supported during the embodiment and detailed design phase. An exception to this is agent-based modeling, which supports conceptual design synthesis [54].

So, the concept matrix indicates that all phases of the design process are represented in literature oriented to KBES and artificial intelligence. Nonetheless, it appears that the early phase, in particular the finding of concepts, is strongly underrepresented. The tasks that are carried out in this phase belong to the “real” engineering tasks of design problem solving which are characterized by open, ill-structured problems that are hard to code in rule sets or in models. Interestingly, no actual literature was found on decision support.

Another point that was surprising is the lack of design automation systems for detailed design. The considered literature indeed discusses design automation, but only on level of the embodiment design. The designer is ought to use the results and further detail the design relying on his experience. Design automation systems that deliver a complete set of drawings and manufacturable artifacts could not be identified.

Regarding algorithms, most of the literature describes newly developed algorithms and their benchmarks. Those are commonly simple standardized experiments like dimensioning and optimizing machine elements, e.g. tension/compression springs, pressure vessels or welded beams [33, 34]. An application to more complex real world problems or multi criteria optimization is usually not covered.

This literature research is not free of limitations. For the literature research we have oriented ourselves on the methodical approach of vom Brocke et al. [14], because in our opinion it supports a traceable and expandable literature review. Even if the literature search follows a systematic methodology, the decisions for the selection of the search phrases and literature sources, as well as their classification, are limited and according to subjective aspects. For a further identification of literature, especially with regard to the late phases of the product development process, a search with further keywords and sources can be helpful. Additionally, the search was a breadth search mainly using Google scholar. A depth search in relevant journals would be complementary. Relaxing the time constraint would also lead to different results.

6 Conclusion and Future Research

This contribution provides a snapshot for the applications of KBES and artificial intelligence in product development that were documented in the last five years in scientific literature. The selected literature focuses on the early phase of the product development process.

With the help of a concept matrix we have assigned 46 relevant articles to the categories methods, tools, processes and design support. By classifying the articles to the product models, a transition to the product development process according to the VDI guideline 2221:1993 is achieved. Our contribution can be used by researchers who are interested in the application of KBES and artificial intelligence in product development, for example to classify their research within the product development process or to derive new research questions with regard to the computer support of developers in the search for solution principles and their structures.

The future research can be oriented at two points from the literature search. Firstly, the concept matrix shows that there is a need for research in order to examine the principles and structures of action using methods of KBES and artificial intelligence. If we consider the entire concept phase of the product development process, functional orientation becomes more and more important. An interesting approach is the transition from function to design.

The second approach aims at the continuous process support of the product development process. Often the support by KBES and artificial intelligence in the literature refers to the embodiment design phase. The detailed design phase is often excluded. In practice, the detailed design phase plays a decisive role in establishing a continuous value-added process.

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